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I, JULIE BILLINGSLEY, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2003903726 for a patent by VENTRACOR LIMITED as filed on 18 July 2003.

WITNESS my hand this
Fifth day of July 2004

J. Billingsley

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Regulation 3.2

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Invention Title: **A Device for Detecting Heart Pumping State**

The invention is described in the following statement:

Our Ref: 031036

A DEVICE FOR DETECTING HEARTPUMPING STATE

Field of Invention

The present invention relates to a device for detecting pumping state of a patient's heart.

Background

Congestive Heart Failure ('CHF') is a disease of great importance. CHF typically results in a deterioration of heart function. A common feature of CHF is that it results in impairment of the performance of the heart's pumping action.

Previously, it has been suggested that the symptoms of CHF can be at least addressed by the use of Left Ventricle Assist Devices ('LVADs') which assist the heart's normal function and reduce the overall pumping load on the heart.

These LVADs typically pump blood from the left ventricle of a heart to a distal region of the circulatory system usually the ascending aorta. One of the main problems associated with use of LVADs is that over-pumping or under-pumping can adversely affect the valves of the heart.

The result of over-pumping or under-pumping is that it places undue stress on the valves which may then break or become a site for thrombogenesis. These events may even lead to further deterioration of the health of a patient and in extreme cases, may lead to the death of a

patient from stroke or formation of blood clots in the circulatory system.

Current controllers which assist in the control of LVADs and related blood pumping devices rely on various sensors to provide information.

Heretofore blood flow and blood pressure have sensors used for control in this context have been placed in contact with the blood stream thereby presenting a site for thromogenesis themselves.

In addition reliability can be a problem in that these devices typically fail because they measure or detect blood flow or pressure invasively within the circulatory system of a patient. Invasively for purposes of this specification means that the device in use is comes in direct contact with the blood of the patient.

As a result, there has been a long felt need for a device and method that non-invasively detects arterial blood pressure and/or arterial blood flow and which is suitable for use in cooperation with a blood pumping device or system.

It is an object of the present invention to address or ameliorate at least one of the above disadvantages.

Brief description of the invention

In a broad form of the present invention, an implantable device is provided for measuring blood flow and/or blood pressure within a blood vessel, wherein said

device, when in use, is positioned to contact the outer surface of a blood vessel within a patient and wherein said device measures blood pressure and/or blood flow within said blood vessel without invasively contacting a patient's blood supply.

Preferably, said device may be adapted to allow the determination of a pumping state of a patient's heart and said blood vessel may be an artery or a vein.

Additionally, said device may be able to determine the pumping state of said heart from changes in said blood pressure or blood flow. It is preferable that the device surround at least a portion of said outer surface of blood vessel and that the device does not occlude or adversely effect the flow of blood or blood pressure within a patient's circulatory system, when in use.

In a preferred configuration, said device may cooperate with a blood pumping system and said device may also contact said vessel at a point downstream from said blood pumping system. The preferred blood pumping system is a left ventricle assist device and may include a centrifugal rotary blood pump and a hydrodynamic bearing surface.

The preferred embodiment of the present invention may include said device with at least one sensor and said sensor may comprise a piezometer, and/or a microphone.

Preferably, a preferred device of may include a cuff which surrounds the said blood vessel, when in use, and said cuff may be non-inflatable. A preferred cuff may comprise a hard plastic ring or a velour ring. The preferred cuff may be fixed to the outer surface of a blood vessel and this fixation may be achieved by application of bioglue, by being incorporated by ingrowth of the patient or by sewing.

The preferred device may provide a voltage output as an analogue of the blood pressure within said blood vessel and said device may also supply data to an implantable blood pumping system and wherein said implantable blood pumping system includes a pump controller which receives said data.

Also according to the present invention, a method for measuring blood pressure and/or blood flow using an implantable device, wherein, in use, said implantable device is positioned to contact the outer surface of a blood vessel within a patient and wherein said device measures blood pressure and/or blood flow within said blood vessel without invasively contacting a patient's blood supply.

This preferred method may include a step for determining pumping states of a heart from said blood pressure and/or said blood flow.

Preferably, said blood vessel with regard to this method is an artery or a vein. According to the preferred method, said device may determine the pumping state of said heart from changes in said blood pressure and/or blood flow. Preferably, said device may also surround at least a portion of said outer surface of blood vessel and preferably this device may not occlude or adversely affect the flow of blood or blood pressure within a patient's circulatory system, when in use.

Also according to preferred version of this method, said device may cooperate with a blood pumping system. The preferred blood pumping system may be implantable and said pumping states may be used to adjust a pumping speed point of said blood pumping system.

Brief description of the drawings

Embodiments of the present invention will now be described with reference to the accompanying drawings wherein:

Figure 1 is a cross-sectional view of a first preferred embodiment implanted within a patient;

Figure 2 is a cross sectional view of a further embodiment attached to an arterial wall;

Figure 3 is a schematic plan of an embodiment cooperating with a blood pumping system;

Figure 4 is a graph showing pumping states of a patient's heart; and

Figure 5 is a schematic drawing of a further embodiment implanted within a circulatory system of a patient.

Brief description of the preferred embodiments

A first embodiment of the present invention is shown within Figure 1. Figure 1 illustrates a portion of a circulatory system of a patient and focuses on the arteries proximal to the heart. Figure 1 additionally features a blood pump, in situ, and preferably this pump may be an implantable centrifugal blood pump suitable for use as a LVAD. A patient's heart 1 is shown to pump blood from pulmonary vein 10 into aortic artery 9 via the left side of the heart. In Figure 1, the heart 1 is shown, for diagnostic purposes, only in reference to this left side of the heart. The left atrium 26 receives blood from the pulmonary veins 10. The blood then flows into the left ventricle 27. Typically, the left ventricle 27 of the heart 1 is responsible for a majority of the pumping blood to a further majority of the circulatory system. In diseases, such as CHF, the left ventricle 27 usually fails or pumps blood poorly. In the past, it has been suggested that left ventricular failure may be treated with the use of a device such as a LVAD. Preferably, a blood pump called VentrAssist™ LVAD may be used for this purpose.

Typically, LVADs require a detection mechanism to detect the physiological condition of the patient. This

detection mechanism may feed back information and data relating to the condition of the patient to the controller mechanism of the LVAD. The controller mechanism may then adjust the pumping rate or speed as required or as necessary. One problem with the traditional LVAD and associated systems is that they may interfere with a patient's normal pulsatile blood flow. This can mean that some patients will experience continuous blood circulation rather than pulsatile blood circulation.

It is preferable for a ventricle to eject blood through all four of the heart valves when a Ventricle Assist Device ('VAD') is present. This may reduce the risk of clot. The particular pumping state resulting from all four other said valves ejecting, usually generates an arterial pulse.

This embodiment of the present invention may provide a non-invasive means by which this state may be detectable. Furthermore, the pumping state information may be fed back into a controller mechanism for a blood pump and further used to adjust pumping speed accordingly.

In the embodiment featured in Figure 1, a patient's circulatory system has been implanted with a centrifugal rotary blood pump 4. This blood pump 4 assists the left ventricle 1 to pump blood into the arteries. The blood

pump 4 is connected to the apex 2 of the left ventricle 1 by stenting or cannulation 3. This stenting provides blood from the left ventricle 1 to the blood pump 4. The blood pump 4 pumps blood to an artery downstream of the left ventricle 1. The blood pump 4 delivers blood to a position 25 by way of an outflow cannula 7. The blood pump 4 is powered and controlled by a percutaneous lead 5 which connects to a pump controller (not shown) and an external power supply (not shown).

The percutaneous lead 5 also supplies the pump with a means of two way data flow to the external pump controller. The pumping speed of the blood pump 4 is controlled by the pump controller. Preferably the blood pump 4 includes sensors which send information to the pump controller and the pump controller uses this information to adjust the pumping speed appropriately.

Alternatively, the controller may be implanted internal to the patient's body, along with an internal rechargeable power supply and a charging system such as a percutaneous lead and/or transcutaneous energy transformer system.

In this embodiment of the present invention, a cuff 8 is placed around a portion of the aortic artery preferably downstream of position 25. The cuff 8 may be secured to the artery by stitching, bioglue, a clip arrangement or by encouraging the patient's body to

incorporate the cuff and thereby embedded it within an outer surface of said artery.

The cuff may be constructed of a significant proportion or a combination thereof of either: hard plastic material, velour, polyetheretherketone ('PEEK'), a biocompatible titanium alloy (for example: Titanium-6 Aluminium-4 Vanadium), polyurethane, polymer and/or graft material. It is also envisaged by this specification that other suitable materials may be used to construct the cuff portion.

The cuff 8 includes at least one non-invasive sensor. This sensor may detect blood flow and/or blood pressure within the artery.

Detection of adverse pumping conditions (eg. suction, fluid flow modulation and fault conditions) affecting a patient's heart may be achieved through analysis of sonic and ultrasonic signals sensed by the. Sensing may be achieved by use of a microphone or vibration sensing means embedded in the cuff portion. This sensor will have no contact with the fluid inside the artery and is therefore "non-invasive" in relation to the circulatory system of the patient. Signals from the acoustic sensing means are sent to the pump controller where by analysis of input can yield a speed set point for the pump. With application to artificial hearts, suction, heart rate and fault conditions can be detected

through analysis of the input means. Avoiding suction provides a step towards providing information for rate responsive artificial control where pump flow is adjusted according to the physical condition of the patient.

In alternative embodiments the cuff 8 can be attached to other veins and arteries. In a further alternatives embodiment, the cuff 8 can be attached to the pulmonary vein for detection of suction events which may be caused by a drain of blood from the pulmonary vein. This drain may be caused by a heart blood pump connected in a similar configuration as that of heart pump 4. In situations where heart pump 4 pumps too much blood from the left ventricle 27 into the aortic artery 9, the aortic valve 54 may remain closed and prevent normal blood circulation in the artery 9 between point 25 and the valve 54. If the overpumping of heart pump is increased, this suction event may afford in the left ventricle 27. The suction event may lead to a mitral valve 53 being in a continuously open position as blood would be drawn directly from the pulmonary vein 10 into left atrium 26 past the mitral valve 53 into the left ventricle and result in a lack of blood pulsatility in the vein 36. These overpumping events are not desirable and should be avoided, if possible. A sensor according to a further embodiment of the present invention connects to the pulmonary vein so as to allow for the detection of

pulsatility within vein 10 and thereby detect whether the blood pump 4 is overpumping blood.

Further embodiments of the present invention can be modified to function with the circulatory system of all mammals. It is envisaged that further embodiments may be suitable for veterinary purposes.

Alternative embodiments of the present invention can function in conjunction with other heart assist devices, blood pump and/or medical devices.

With reference to Figure 1 there is illustrated in diagrammatic form a blood pump 4 installed within the human body and arranged to function as a left ventricular assist device. The pump 4 is arranged to operate in parallel with blood flow passing through left ventricle 27. This is effected by inserting an inlet cannula 3 into left ventricle 27 and directing blood flow through the inlet cannula into an inlet of blood pump 4. Blood pump 4, in operational mode, pumps the blood thus received into aorta 9 via outlet cannula 7, as illustrated in Figure 1.

The blood pump 4 can take a number of forms and rely on a number of different pumping and drive technologies. Broadly, the pump technology can be based on axial or centrifugal rotary pump arrangements or on positive displacement technologies.

In particular, although not limiting forms, preferred pumping technologies for the control system to be described below include rotary pump technologies which rely on an impeller supported for rotation within a casing and which causes blood to be urged between an inlet and outlet of the casing as the impeller rotates therein. In more particular preferred forms a centrifugal form of pump can be utilised with the control system with the characteristics of the pump tailored to compliment or otherwise work particularly advantageously with the control system according to various embodiments of the present invention.

Typically, the pump 4 is driven by an electrical power source. In relation to the embodiment shown in Figure 1 the device is powered by a battery pack mounted externally of the body. Electrical power from the battery pack is controlled by a controller unit also mounted externally of the body. In addition to communicating electrical power to the pump 4 the controller can also communicate with an external programming source. This external programming source may be a personal computer for the purposes of initial setup and ongoing periodic monitoring and recalibration of the pump and controller as customised for a specific patient.

In Figure 2, a second embodiment of the present invention is shown. Cuff 12 is wrapped around the outer

surface of artery 11. Two sensors 13 are integrally joined with the cuff 12. The two sensors 13 are preferably mounted so as to allow direct contact with the outer wall of the artery 11.

The two sensors 13 may measure blood flow or pressure at a position close to where they contact the outer wall of the artery 11. It may be preferable, to have two sensors so as to provide a differential pressure measurement between the two positions of the sensors.

The measurements gained from the sensors 13 may be feed back to the pump or pump controller depending on the configuration of the medical device for which the present embodiment is attached. Signals and data from the sensors 13 delivered to other devices by the sensor lead 14.

According to a further embodiment, shown in Figure 3, the arterial cuff 20 includes a sensor means 21. This sensor means 21 supplies data and information relating to the circulatory system of the patient to a pump controller 16.

This pump controller 16 is supplied with power from a power source 15. This power source 15 may be batteries or regular mains power. The pump controller 16 receives input data and information from the motor controller 17 in the forms of a power sensing means 24 and speed sensing means 23 and input data from the sensor means 21. The pump controller 16 then calculates an appropriate

pumping and feeds speed set point data 22 to the motor controller 17.

The motor controller 17 controls the actuations of the pump motor 18 located within the pump body 19. Preferably the pump body 19 and the arterial cuff 20 are implanted within the patient's body. The pump motor 18 preferably functions as a heart assist device. However other extended uses of the pump motor 18 may be possible.

Figure 4, shows the various cardiac pressure outputs plotted against time as measured within the aortic artery. A normal cardiac pressure output is shown by line 29. Line 29 demonstrates a typical person's pressure output, please note that this person does not have an implantable continuous flow LVAD. Line 28 graphically displays the pressure output of a similar person, as shown in line 29, wherein a continuous flow LVAD is implanted and is actively assisting the heart. Position 31 shows the point at which the aortic valve opens and position 30 shows the position at which the aortic valve of the patient's heart closes. It can be seen that the LVAD raises the baseline pressure within the artery and thereby reduces the pulsatility of the patient's circulatory system. The reduction of pulsatility may lead to problems in externally detecting the patient's condition in the traditional ways.

In a further situation, a similar patient, to the one displayed in 29, is implanted with a continuous flow LVAD and the LVAD as shown by line 32 is pumping at a higher pressure than the pumping pressure of the heart. Thereby the aortic valve is not opening and closing and the pulsatility is completely removed. In this situation, embodiments of the present invention may be able to detect blood flow and pressure rates whereas tradition methods would fail to detect the patient's condition.

Figure 5 shows a further embodiment of the present invention as a schematic outline. Figure 5 shows the circulatory system of a patient. In this figure, oxygenated blood flows from the left atrium 43 of the heart into the left ventricle 42 where the blood is pumped into the aorta 36. The aorta connects to other arteries in the upper body 35 and arteries in the lower body 50. Thereby oxygenated blood is delivered to the entire body by relying on blood pumping pressure supplied by the left ventricle 42.

The oxygenated blood is then utilised by the head 34 and organs and muscles in lower body 51. The deoxygenated blood is then delivered to veins from the upper body 33 and/or veins from the lower body. The deoxygenated blood then travels along these veins to the vena cava 51 which turn supplies the oxygenated blood to the left atrium 40 of the heart. The right ventricle 41 pumps deoxygenated

blood into the pulmonary artery 44. The blood then travels to the lungs 37 where it is re-oxygenated. The oxygenated blood then returns to the left atrium 43 of the heart via the pulmonary vein 38.

Also in Figure 5, an implantable blood pumping apparatus 47 is shown. This apparatus 47 is connected to the apex of the left ventricle 42 by way of an inflow cannula 48. The apparatus 47 pumps blood into the outflow cannula 49 and this outflow cannula delivers the blood to the aorta 36.

In this embodiment, a cuff apparatus is non-invasively attached to the aorta 36 and is connected to the pump by lead 46.

It is also possible to attach embodiments of the present invention to other regions of the circulatory system without deviating from the original spirit and scope of the present invention.

Methods were also developed to detect pumping states based on the measurements obtained from the abovedescribed embodiments. The methods developed allow impeller speed and pump input power to be freely modulated by ventricular contractions. This dynamic information is utilised as feedback to the control system. Data from in-vitro and in-vivo experiments shows that states such as Total Ventricular Collapse ('TVC') and Pump Regurgitation ('PR') produce low flow through

the pump. State TVC produces non-pulsatile low flow while PR produces pulsatile low flow less than 1 L/min. States such as Partial Ventricular Collapse ('PVC'), Aortic Valve Closed ('AC') and Ventricle Ejecting ('VE') produce normal pump flows greater than 1 L/min. States PVC and PR can be differentiated from state AC since flow pulsatility is more evident. State PVC can be differentiated from state VE since the dynamic flow profile is different from all other states. The dynamic nature of the flow is reflected by intravascular blood pressure and/or intravascular blood flow.

Instantaneous measured pump speed is used to indicate flow dynamics.

Examining the in-vitro and in-vivo that it has been found that state TVC can be consistently detected by a fall pump flow to near 0 L/min accompanied by a reduction of flow pulsatility. It has been observed that the flow waveform profile may not be relevant for detection of this state.

The state PVC is indicated by a variation in profile of the instantaneous speed waveform given a level of pulsatility. Given that normal flow rates can still be observed during this state and that flow pulsatility is large, the only parameter distinguishing this state from the VE state is the flow profile.

By analysing the cardiac cycle with the pump it has been found that there may be a portion of state AC where the aortic valve remains closed, whilst however the pump flow is still pulsatile. This portion defines a point beyond which pump flow pulsatility may be reduced. At high perfusion demands, as in exercise, the failed ventricle may be supplemented to such an extent that the flow through the pump is pulseless. Theoretically if no left ventricle contraction occurs then implantable rotary blood pump flow will be non pulsatile. Contraction of the left ventricle with the pump connected means that pump head is proportional to the difference between the aortic pressure and the Left Ventricular Pressure ('LVP'). If the pump power is increased beyond the point that the left ventricle is doing no work (the aortic valve no longer opens) maximum LVP begins to decrease. This means that the minimum instantaneous pump differential pressure will begin to rise relative to the RMS of the pump differential pressure over the cardiac cycle. If the ventricle is weakened through heart failure this will occur at relatively lower pump speeds and the mitral valve will still continue to open and LVP maximum will decrease towards zero with increasing speeds. During this interval the mitral valve will open and close. Steady flow occurs when there is no pulsatility in the speed signal and the mitral valve never closes. The target

speed at which this occurs will increase with SVR or VR and cardiac contractility. Continuing to increase the pump power will cause the transition from pulsatile to non pulsatile flow. This means detection of the state VE and state AC can only AC can only be achieved dynamically by considering the maximum instantaneous speed Nmax (t) and the rms of instantaneous speed Nrms(t) for the nth and (n-1)th cardiac cycle. A significant change occurs only if there is a change in average pump speed set point, after load or pre-load. A method of detecting the AC state without relying on transitions has been chosen which uses peak to peak flow rate that pump flow is greater than 1L/min.

State VE may be identified non-invasively by pump flow rate being larger than 1L/min and peak to peak instantaneous voltage (flow) being greater than a threshold value and the flow symmetry being greater than that for the PVC state.

The PR state may be indicated when the pump flow falls below the lower flow limits Qmin which is set to be 1 L/min. This level of Qmin is set at 1 L/min although not "0L/min"may be considered a safe limit to be classed as retrograde flow.

By analysing pump parameters deriving from invasive derived parameters it is postulated that flow, flow amplitude and profile appear to be good indicators of

pumping state using only non-invasively derived pump parameters. These variables can be detected non-invasively using the above described embodiments of the present invention.

The above description only describes some of the embodiments of the present inventions and it will be obvious to those skilled in the art that further modifications can be made thereto without departing from the scope and spirit of the present invention.

Claims

1. An implantable device for measuring blood flow and/or blood pressure within a blood vessel, wherein said device, when in use, is positioned to contact the outer surface of a blood vessel within a patient and wherein said device measures blood pressure and/or blood flow within said blood vessel without invasively contacting a patient's blood supply.

2. The device of claim 1 wherein said device is adapted to allow the determination of a pumping state of a patient's heart.

3. The device of any one of claims 1 or 2 wherein said blood vessel is an artery.

4. The device of any one of claims 1 or 2 wherein said blood vessel is a vein.

5. The device of any one of claims 1 to 4 wherein said device determines the pumping state of said heart from changes in said blood pressure.

6. The device of any one of claims 1 to 5 wherein said device determines the pumping state of said heart from changes in said blood flow.

7. The device of any one of claims 1 to 6 wherein said device surrounds at least a portion of said outer surface of blood vessel.

8. The device of any one of claims 1 to 7 wherein said device does not occlude or adversely effect the flow

of blood or blood pressure within a patient's circulatory system, when in use.

9. The device of any one of claims 1 to 8 wherein said device cooperates with a blood pumping system.

10. The device of claim 9 wherein said device contacts said vessel at a point downstream from said blood pumping system.

11. The device of claim 10 wherein said blood pumping system is a left ventricle assist device.

12. The device of claim 11 wherein said blood pumping system includes a centrifugal rotary blood pump.

13. The device of claim 12 wherein said centrifugal rotary blood pump includes a hydrodynamic bearing surface.

14. The device of claim 8 wherein said device includes at least one sensor.

15. The device of claim 8 wherein said sensor comprises a piezometer.

16. The device of claim 8 wherein said sensor comprises a microphone.

17. The device of claim 8 wherein said device includes a cuff which surrounds the said blood vessel, when in use.

18. The device of claim 8 wherein said cuff is not inflatable.

19. The device of claim 8 wherein said cuff comprises a hard plastic ring.

20. The device of claim 8 wherein said cuff comprises a velour ring.

21. The device of claim 8 wherein said cuff is fixed to the outer surface of said blood vessel.

22. The device of claim 8 wherein said cuff is fixed by application of bioglue.

23. The device of claim 8 wherein said cuff is fixed by the surface of the cuff being incorporated by ingrowth of the patient.

24. The device of claim 8 wherein said cuff is fixed by sewing.

25. The device of claim 8 wherein said device provides a voltage output as an analogue of the blood pressure within said blood vessel.

26. The device of claim 9 wherein said device supplies data to said implantable blood pumping system and wherein said implantable blood pumping system includes a pump controller which receives said data.

27. A method for measuring blood pressure and/or blood flow using an implantable device, wherein, in use, said implantable device is positioned to contact the outer surface of a blood vessel within a patient and wherein said device measures blood pressure and/or

blood flow within said blood vessel without invasively contacting a patient's blood supply.

28. A method of claim 27 wherein said method includes a step for determining pumping states of a heart from said blood pressure and/or said blood flow.

29. The method of any one of claims 27 or 28 wherein said blood vessel is an artery.

30. The method of any one of claims 27 or 28 wherein said blood vessel is a vein.

31. The method of any one of claims 27 to 30 wherein said device determines the pumping state of said heart from changes in said blood pressure.

32. The method of any one of claims 27 to 31 wherein said device determines the pumping state of said heart from changes in said blood flow.

33. The method of any one of claims 27 to 32 wherein said device surrounds at least a portion of said outer surface of blood vessel

34. The method of any one of claims 27 to 33 wherein said device does not occlude or adversely affect the flow of blood or blood pressure within a patient's circulatory system, when in use.

35. A method of claim 34 wherein said device cooperates with a blood pumping system.

36. A method of claim 35 wherein said blood pumping system is implantable.

37. A method of claim 36 wherein said pumping states are used to adjust a pumping speed point of said blood pumping system.

38. An implantable device herein described with reference to accompanying Figures 1, 2, 3 or 5.

Dated: 18 July 2003

Ventracor Limited

By their Patent Attorneys

WALLINGTON-DUMMER

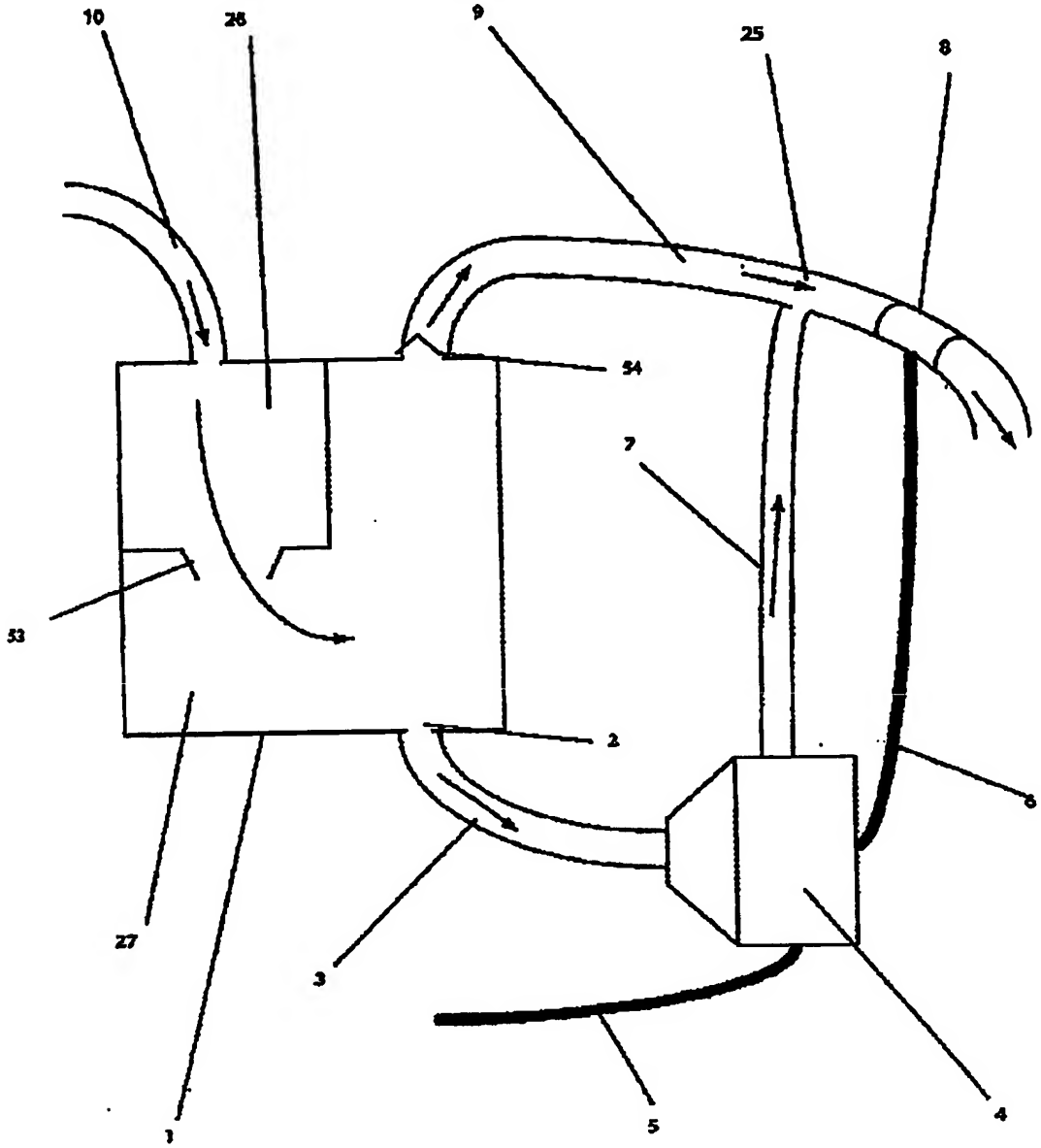


Figure 1

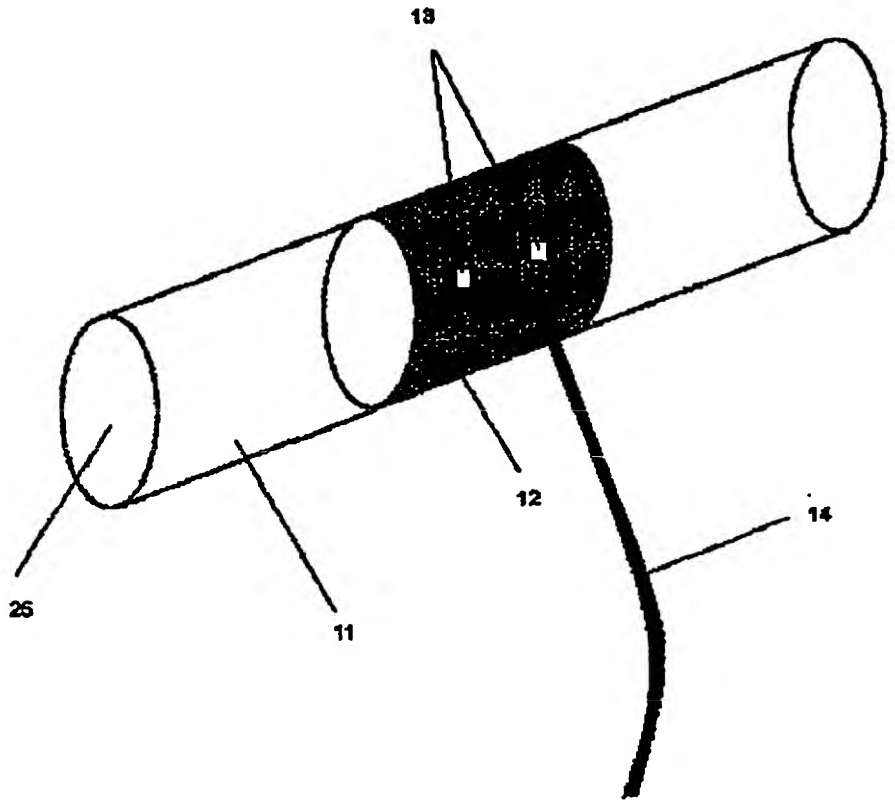
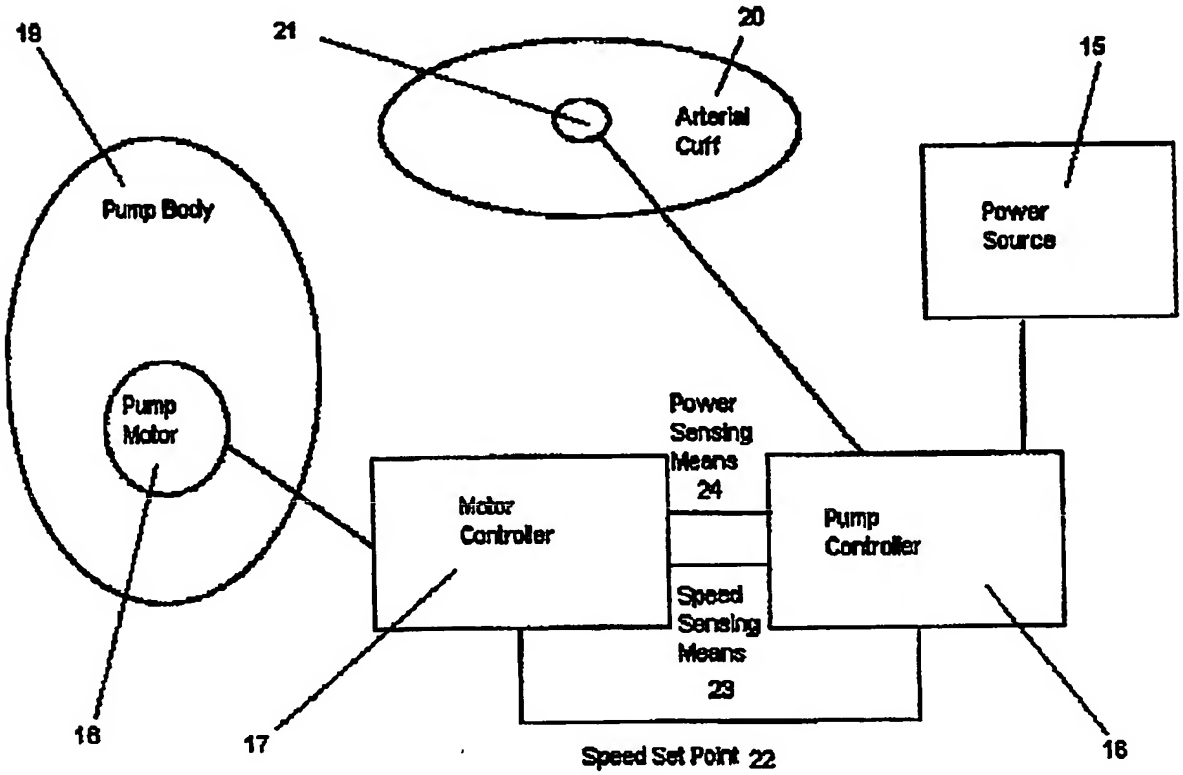


Figure 2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Arterial Cuff
Pump Body
Power Source
Pump Motor
Power Sensing Means 24
Motor Controller
Pump Controller
Speed Sensing Means 23
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Speed Set Point 22
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Figure 3

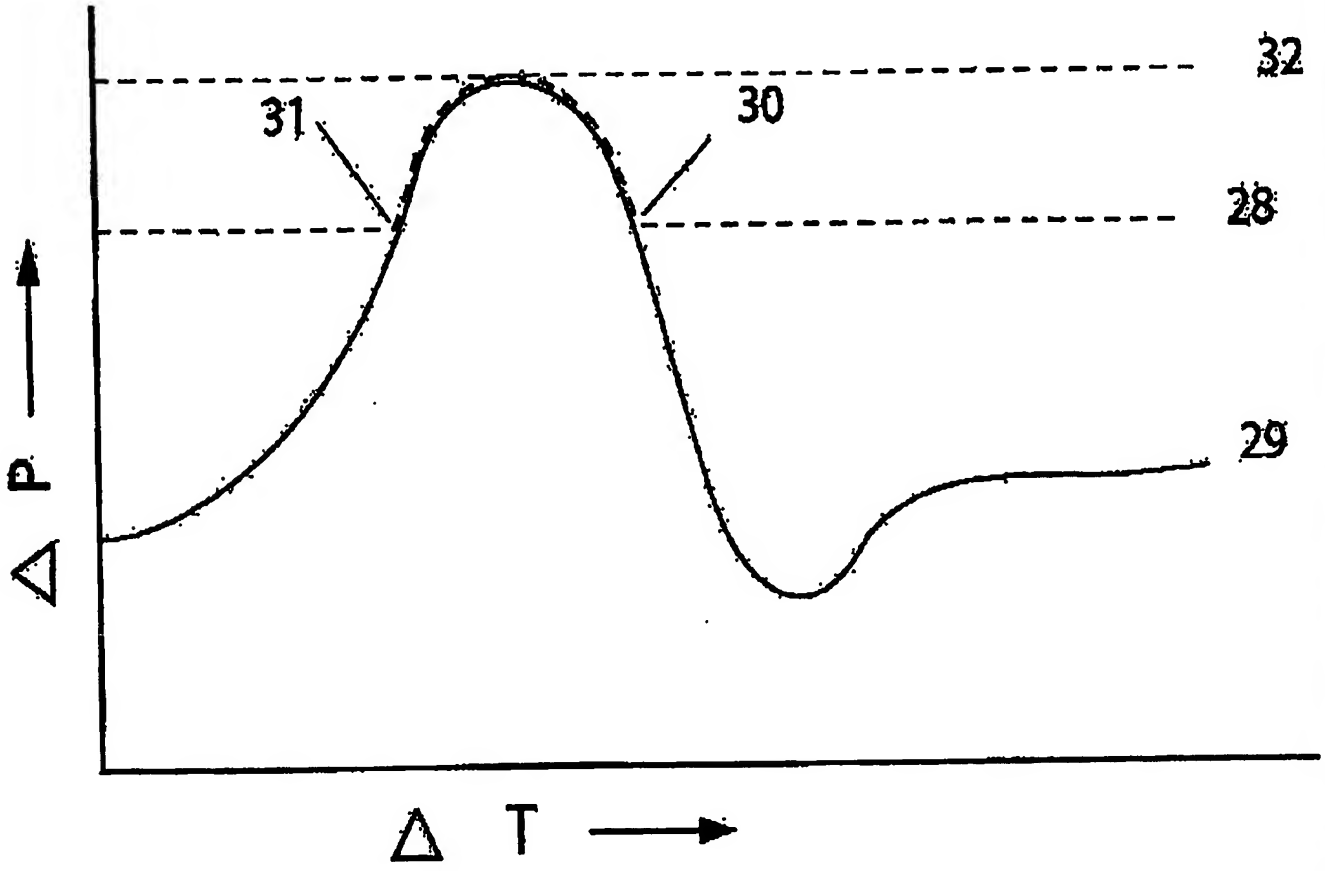

Figure 4

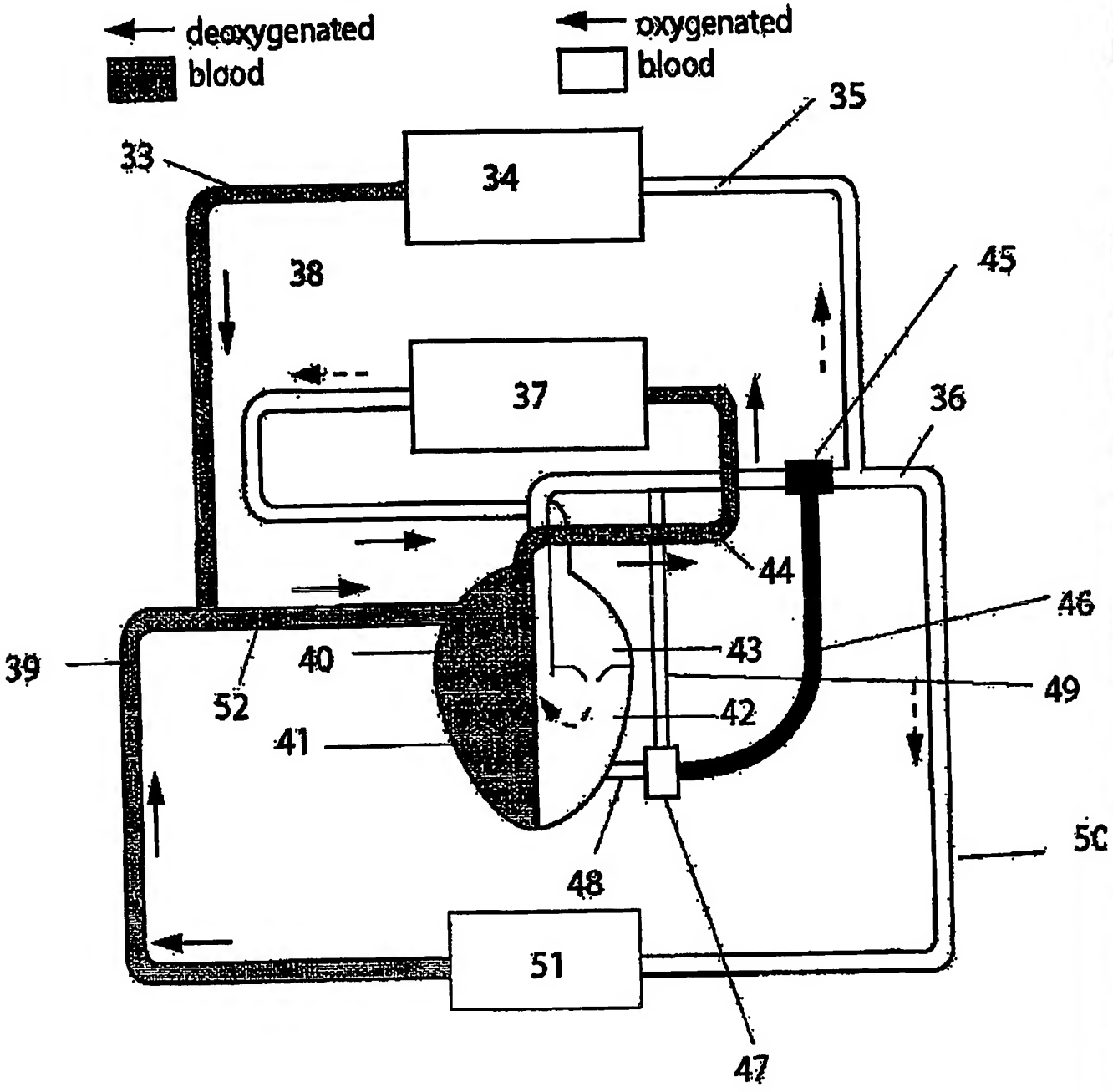
deoxygenated blood
oxygenated blood
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Figure 5